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Water movement in the top layers of soil*

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ABSTRACT. In the unsaturated soils of top layers, adsorption of water vapour takes place. Vapour pressure gradient in top layers of soil creates a gradient of adsorbed moisture. Hence moisture will be transferred by surface due to the gradient of the adsorbed molecules. This is in addition to volume transfer.

1. Introduction

Movement of water in the layers of soil above the capillary head** is not fully understood. Water moves as liquid from water table up to the capillary head. According to the generally accepted view, the movement of moisture above the capillary head is in the form of vapour and liquid and according to this view the only mode of transfer in the very unsaturated soil is by vapour diffusion. But volume diffusion was not able to account for the total observed transfer through the layers above the capillary head.

Bodman and Colman (1942) have confirmed that in certain soils capillary movement does take place at less than 'moisture equivalent' moisture content. Winterkorn (1947) stated that there is film movement in soils, whose soil air humidity is below 100 per cent. It seems reasonable that he explained surface diffusion as film movement, more so because he considered the movement of water adsorbed at relative humidity lower than 100 per cent as stated above. Marshall and Gurr (1954) studied the movements of dissolved chlorides and concluded that movement of liquid water takes place even when the moisture content of the soil is below wilting percentage. The liquid water movement they observed at and below the wilting percentage must be by some other mechanism other than capillary movement in the usual sense. Taylor and Cavazza (1954) and Rollins and Spangler(1954) stated that there is some other mechanism of water transfer other than volume diffusion in unsaturated soils. They had to arrive at this conclusion in order to explain the large water transfer they observed. In order to get more insight into the mechanism of water transfer, the author did a number of experiments.

2. Experiments

(A) Uniformly packed soil samples were kept in transparent glass or plastic tubes of length about 75 cm and 4·3 cm diameter. Then the wet front (the visible boundary between the moist and dry soil) motion produced by free or limited supply of water or concentrated salt solution from the bottom of the soil column at a constant pressure head was studied. The top of the soil column was exposed to different humidities. The sketch of the arrangement for such a study is shown in Figs. 1 and 2 (see Table 1).

(B) An experiment was done to study the effect of gravity on the wet front movements by supplying a limited supply of water to the centre of the vertical column of uniformly packed soil. Sandy soil was used in most of the experiments. Details of the experiments are given in Tables 1 and 1(a) (see Fig. 1a).

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**Capillary head is the level in soil column whose height above water table is equal to the height of water column that can be supported by the capillary pull of the soil and is found by the method described by Puri (*see reference*).

TABLE 1

Wet front motion is sandy soil

Experiment number	Amount of liquid supplied at the lower end and R.H. of liquid	Height of wet front above the free water surface or the base of the tube (cm)	Number of days taken for the rise	Remarks
1	Con. soln. of NaCl R.H. 75% Free supply	25·1	1	Sandy soil, top exposod to 53% R.H. After 90 days the capillary column broke.
		36·6	10	
		37·2	20	
		37·7	30	
		38·5	90	
2	Con. soln. of $Mg (NO_3)_2. 6H_2O$ R.H. 53% Free supply	20·6	1	Sandy soil, top exposed to 53% R.H.
		32·0	10	
		34·7	20	
		36·0	30	
		38·3	120	
		38·3	200	
3	3 gm water R.H. 100%	4·0	1	Sandy soil, top exposed to 53% R.H.
		6·0	10	
		9·0	30	
		Diffused front, no trace of water	50	
4	3 gm of con. soln. of magnesium acetate	4·2	1	Sandy soil, top exposed to 53% R.H.
		6·4	10	
		7·4	30	
		8·1	90	
		8·2	100	
		8·1	160	
5	1·4 gm of $Mg (C_2H_3O_2)_2$ con. soln. R.H. 65%	3·1	1	Sandy soil, top exposed to 65% R.H.
		4·0	10	
		4·4	20	
		4·7	40	
		4·8	80	
		4·8	200	
6	Free supply of water R.H. 100%	22·0	1	Soil consisting of 50% of 0·75 mm and 50% of 0·15 mm particles. Top exposed to R. H. of 53%
		36·0	10	
		39·0	20	
		41·0	30	
		46·5	150	
		Front diffused	160	

TABLE 1 (a)

Wet front motion in sandy soil

Experiment number	Amount of liquid supplied at the lower end and R. H. of liquid	Distance moved by wet fronts		Days
		Upward (cm)	Downward (cm)	
1	10 gm of water supplied at the centre of a column of soil	3·2	6·5	1
		3·4	6·8	2
		3·6	7·0	3
		4·0	7·4	4
		4·1	7·5	5
		4·2	7·7	6
		4·5	7·9	7
		4·7	8·1	8
		4·8	8·2	9
		4·9	8·3	10
		4·9	8·3	11
				Started to diffuse
2	1·4 gm of water	3·7	1	Sandy soil, top exposed to 100% R.H.
		5·0	10	
		5·3	15	
		Diffused front, no visible trace of water	20	
			30	
3	1·4 gm of con. soln. of $MgCl_2$ R.H. 32%	2·9	1	Sandy soil, top exposed to 32% R.H.
		4·0	10	
		4·8	20	
		5·3	40	
		5·8	60	
		6·3	100	
		6·6	130	
		6·9	200	
4	Free supply of water R.H. 100%	19·0	1	Sandy soil
		25·0	2	
		36·5	10	
		41·2	20	
		44·5	30	
		46·2	40	
		47·5	70	
		Experiment was stopped		

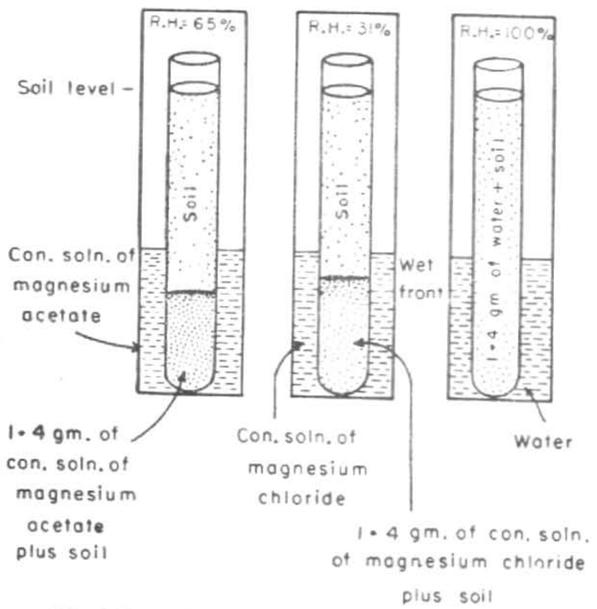

Fig. 1. Apparatus to show the effect of zero gradient in relative humidity

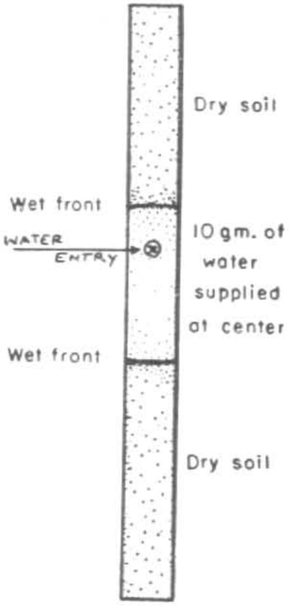

Fig. 1(a). Apparatus to show the effect of gravity on wet front

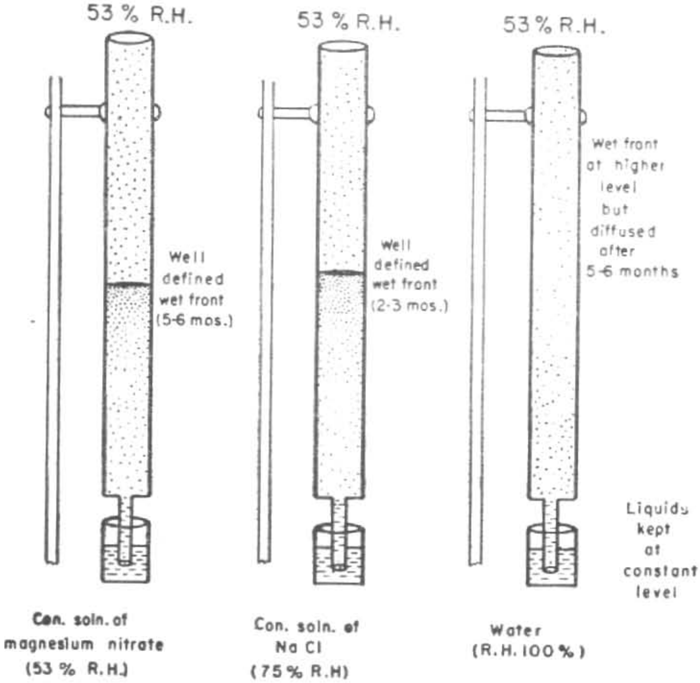

Fig. 2. Apparatus to show the effect of relative humidity gradient

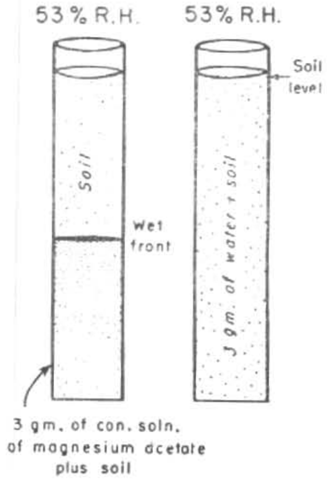

Fig. 2(a). Apparatus to show the effect of humidity

TABLE 2

Typical data for the rate of water intake as read by the burette

(April 1957)

Date and time	Reading on the burette (cc)	Date and time	Reading on the burette (cc)
1 0900	4·0	13 0900	14·7
2 0900	6·0	14 0900	15·2
3 0900	7·1	15 0900	15·4
4 0900	8·1	16 0900	16·4
5 0900	9·1	17 0900	16·8
6 1000	9·6	18 0900	17·5
7 0730	10·5	19 0900	18·2
8 0900	11.5	20 0900	19·0
9 0900	12·5	21 0900	19·8
10 0900	13·0	22 0900	20·4
11 0900	13·7	23 0900	21·2
12 0900	14·3	24 0900	22·0

(C) Two plastic tubes (length 92·5 cm and diameter 20·3 cm) containing soil were also used to study the wet front motion. The transparent plastic tubes were very useful in studying the different moisture regions and boundaries formed in the soil after steady state was reached. One of the large plastic tube contained sand of diameter 0·77 mm and the other contained sandy soil (mixture of Columbia river soil, blasting sand of average diameter 0·15 mm and loam). While filling the plastic tubes with soil, every care was taken to see that weight per unit height of the soil column remained constant. Thus the porosity of the soil was taken as uniform throughout the soil column before adding the water. Water was supplied to the soil column from the bottom keeping the pressure head constant. Experiments with sand column in the large plastic tube were started in the month of April 1956 and with sandy soil were started in the month of January 1957. Steady state was attained by sand in about a month and that for sandy soil took about seven months. Soil moisture determination was made in the month of February 1958. The criteria for the steady state are given below. Soil was supposed to have attained steady state when the daily water intake became constant and when the wet front (the common boundary between the dry and moist soil) remained at a constant depth below the surface of the soil column. A typical data of water intake into sand is given in Table 2.

The room temperature was kept at constant temperature by means of a thermostat and at constant humidity by exposing 36 sq. ft of magnesium nitrate (concentrated solution) to the air inside the room. A typical chart of the daily thermo-hygrograph record is shown in Fig. 3. It is clear from the figure that temperature did not vary more than ±1°F and the humidity did not vary more than ±1 per cent.

3. Observations

After steady state had been reached in the case of sandy soil in the large plastic tube, many different moisture boundaries were observed in the soil column. They are the water table, the capillary head, the wet front and the surface of the soil column. The soil in between the water table and the capillary head is saturated and looks wet and dark. The soil in between capillary head and wet front looks drained, moist and slightly dark and that in between wet front and surface of the soil column looks dry and is of light colour. These layers are shown in Fig. 4. During the experiment with soil in the large plastic tubes it was observed that dirt was deposited at the capillary head. Above that level water movement is not precisely in the liquid form. Moisture analysis also showed that moisture content decreases rapidly up to the capillary head and then with increasing distance above the free water surface, the moisture content decreases more or less uniformly. Moisture content with height is given in Table 3. Somewhat similar variation of moisture content with height above water table is shown in Baver's soil physics (Fig. 45, page 230). Mallik (1942) measured

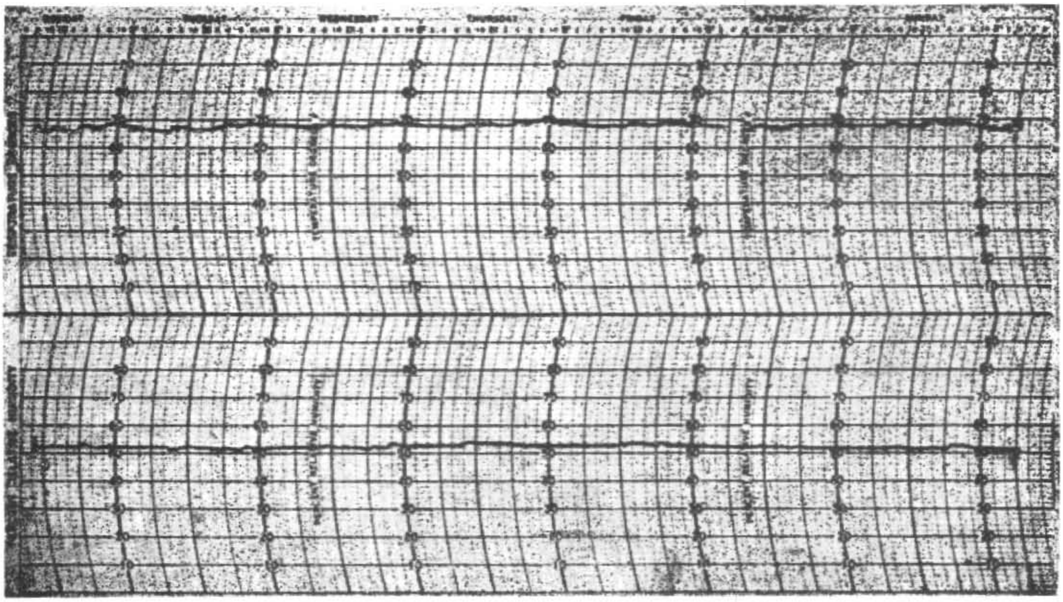

Fig. 3. A typical chart of daily thermo-hygrograph of University of Washington for the period 7—14 April 1957

TABLE 3

Moisture percentage with depth

Depth below the surface (cm)	Moisture percentage (gm/100 gm)	Depth below the surface (cm)	Moisture percentage (gm/100 gm)
SANDY SOIL		SANDY SOIL	
0	0·93	47·0	26·30
2·5	2·91	50·0	29·93
5·0	5·00	52·0	32·40
10·0	6·18	SAND	
15·0	7·18	1·0	0·010
20·0	7.98	5·0	0·011
25·0	9·63	10·0	0,021
30·0	11·04	14·0	0·030
35·0	11·90	19·0	0·049
40·0	13·24	25·5	0·075
45·0	15·66	30·0	32·5

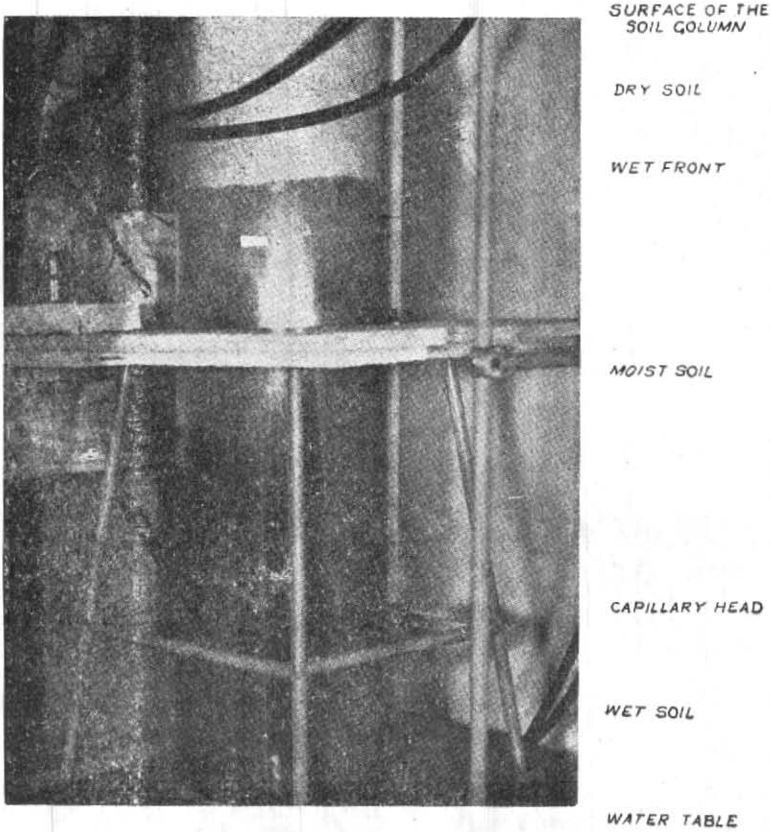

Fig. 4

the moisture content of Punjab alluvial soil with height above the water table, but did not observe any rapid variation at any level. It seems from Mallik's data that the soil column he analysed was wet throughout, whereas the soil, the author analysed consisted of wet, moist and dry soil.

Considering the other experiments (A) mentioned above, it was observed that after an initial rise of liquid up to the capillary head, the wet front moved further up, depending on the liquid. The wet front formed by salt solutions gradually came to a stationary level, but that formed by water moved further up with time. Then with passage of time the wet front formed by water gradually diffused. Throughout the experimental period (*vide* Table 1) the wet front formed by salt solutions were well defined.

On studying the effect of gravitation on the wet front by supplying a limited amount of water at the centre of a soil column of uniform packing, it was found that once the gravitational water has moved the wet fronts (lower and upper) motion was independent of gravitational effect. Fig. 5 shows the motion of the two wet fronts. They moved in opposite direction with equal speed and with time the fronts diffused.

4. Discussions

During the experimental studies with sandy soil (Experiments A and C), it was found that after an initial rapid rise the wet front continued to move upward slowly at a

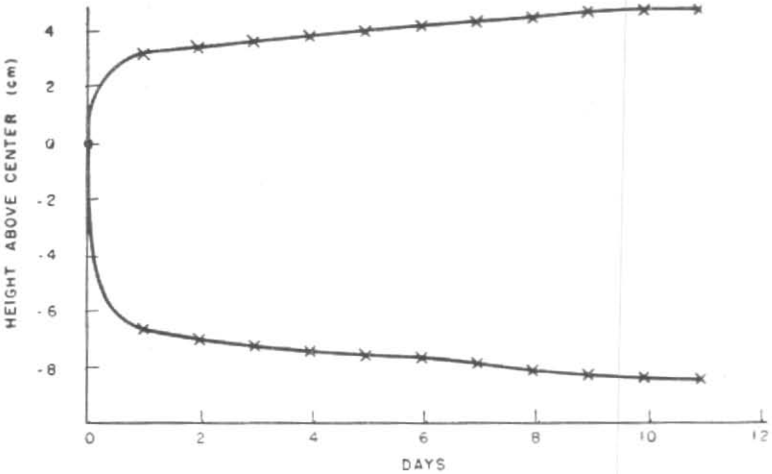

Fig. 5. Wet front movement-effect of gravity

constant rate till it came up to 3 or 4 cm below surface of the soil column. Initially it was thought, that the phenomenon being observed was the movement of capillary water and that frictional retardation was causing it to move slow. This frictional retardation can be caused by swelling of soil particles or by entrapped air blocking the capillary. However, this explanation was rejected and concluded that adsorbed vapour caused the movement of the moist layer. Some reasons are given below—

(1) Since the clay content of the soil was very small, there cannot be much swelling.

(2) Average particle size of the soil used was large enough to produce capillaries which will not entrap air particularly when water is rising from below.

(3) The slow movement was also not due to the change of angle of contact due to decrease in moisture content. Van't Woudt (1954) has shown that increase in moisture content is not related to lowering of angle of contact. In general capillary movement is confined to condition to which moisture content of the medium is quite close to saturation value.

(4) By the conventional experiment described by Puri (see ref.) it was found that the capillary head was only 20 cm above the free water surface. But it was observed that the soil was moist up to a height far above the capillary head.

(5) Ramdas and Mallik (1942) have shown that sodium chloride and nitrates do not cause swelling.

(6) Supposing that the wet front motion is due to capillary rise of liquid, then the soil column having supply of salt solutions such as magnesium nitrate and sodium chloride from the bottom should have higher capillary rise than those supplied with water. This should be so, because the surface tension of the salt solutions used is greater than that of water. This is exactly what was observed in the first few days. Ramdas and Mallik (1942) also observed similar results. But with time it was observed (*vide* Table 1) that the wet front in soil column supplied with water was at a higher level than that supplied with salt solutions.

(7) It was observed that the downward and upward moving wet fronts moved at equal speeds, after the gravitational pull on water has lost its effect. This means that motion at this stage is not due to capillarity in the usual sense. In this connection it may be mentioned that Veihmeyer (1927) found that the upward and downward movement of moisture into dry soil from a soil at field capacity is almost same. The wet front motion can be explained as follows.

On close examination of the experimental results, it was noticed that the height of the wet or moist column was independent of the liquid used during the first few days of the experiment. After the first few days the rise of the moist column was no longer independent of the liquid used. This means that when liquid is supplied from the bottom of a dry soil column, first the liquid rises up to the capillary head. Hence the salt solutions used will rise more because of they have higher surface tension. The time for the rise will depend on the soil used. In the case of sand and sandy soil used the time was only a few days. During this time the soil above the wet or the moist level will be adsorbing vapour depending on the relative humidity of the vapour. The relative humidity of the vapour in equilibrium with the salt solutions are much lower than that of water. When humidity is high above the moist level, then sufficient water molecules are adsorbed in soil above moist layer, the soil will become moist and thus moist layer will rise. But on the other hand when humidity is low above the moist level, the absorbed molecules on the soil particles above the wet layer is not enough to moisten them. In general this will be the case, above the moist column produced by salt solutions.

This implies that the vapour pressure gradient above moist level produced by water will be strong and that above the moist layer formed by salt solution will be weak. Hence the effect could be tested in soil supplied with limited supply of water and salt solution. It was found (*vide* Table 1) that moist level produced by water diffused with time showing that there is more evaporation from such level because of the strong vapour pressure gradient. On the other hand the evaporation from the moist level formed was less because of the low vapour pressure gradient and hence the moist level remained well defined. Ramdas and Mallik (1939) found that loss of water from "Bari" soil (alkali soil containing large percentage of salt) is strikingly smaller than that from either normal Punjab soil (alluvial soil) or black cotton soil of Poona for all depths of water table. Mallik (1942) found that only a short column of "Bari" soil was wetted when compared to the other two soils, even after many months. The explanation given above will make clear the observations of Ramdas and Mallik. Stern and Shinad (1958) studied the diffusion of a solution into another solution kept in the interspaces of small glass beads. He found that there exists a lower limit of concentration below which the diffusing front does not advance at all, because diffusion into the beads uses up all the diffusing solution. In the soil also there exists a lower limit of concentration of water vapour, below which the wet front does not advance at all, because the diffusion into the dry soil uses up all the diffusing molecules.

5. Conclusions

Wet front motion takes place only when ample molecules have been adsorbed by the soil surface. In other words, wet front motion takes place only when there is multimolecular adsorption on surface of the soil particles above the wet front. If the humidity is low there will be no multimolecular adsorption and hence no movement of wet front occurs.

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